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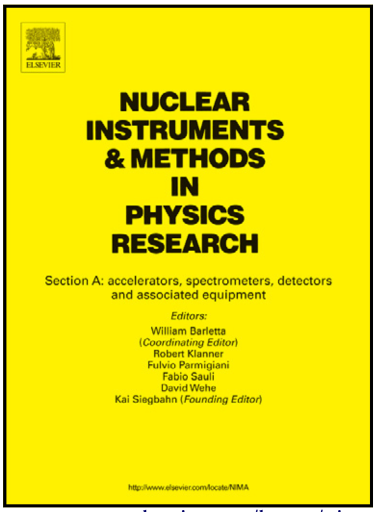

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Operating Hybrid Photon Detectors in the LHCb RICH Counters at High Occupancy

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Abstract

We report about the experiences in the operation of the Hybrid Photon Detectors in the Ring Imaging Cherenkov Detectors of the LHCb experiment during the first run period, 2010-2012. Of particular interest is the ageing due to the deterioration of the vacuum quality of the tubes, leading to an increase of ion feedback.

Key words: Cherenkov counters, Hybrid Photon Detectors, Ion Feedback, LHCb RICH

1. Introduction

During the Run I of the LHC (2010-2012) the LHCb experiment [1] has operated about 500 Hybrid Photon Detectors [2] (HPD) in its Ring Imaging Cherenkov (RICH) detectors. In this time the experiment continuously has ramped up its data taking performance. In 2012 LHCb has run at twice its design luminosity ($\mathcal{L}$=4*$10^{32}/cm^2/s$), at four times the design value of the visible interaction rate per bunch crossing ($\mu = 1.6$) and at a High Level Trigger output rate to tape which was a factor of 1.5 higher than in 2011 (4.5kHz), while an overall data taking efficiency of > 95 % was achieved. In order to push the key data taking parameters to the limits in this way all sub-detectors had to be optimised to the very best of their performance. Following up on our first running experiences [3] here we report about the key parameters of this process for the LHCb RICH detectors, with particular focus on the performance of the photon detectors.

2. Hybrid Photon Detectors

HPDs are still unique in combining a vacuum photon detector with a silicon pixel readout, where the first level of readout electronics [4] is embedded in the vacuum. Extensive tests after production [5, 6] established the trust in this technology and confirmed the expectations put into its performance. Three parameters were key for this choice. The internal demagnification enables close packing to an overall active area fraction of the system of 65 %. The high Quantum Efficiency peaks in the UV where it is most useful to us. An added benefit was that the global average of the production sample increased over time to a final value of 30.8 % at 270 nm. And finally the low noise of the silicon pixel readout is leading to an average signal-over-noise of 27 at 20 kV and causing very low background. Only after the time scale of several years of operation it turned out that the HPDs were susceptible to vacuum degradation leading to the development of an increased ion feedback (IFB) [7]. While operation during Run I confirmed all the strengths of the technology we now have developed a fix for its draw-back, promising to suppress the vacuum degradation for significantly more years than the projected lifetime of the experiment (until 2018).

3. Experiences from Run I

The major challenge for the RICH detectors over Run I was to cope with the occupancy steadily increasing during 2010 and 2011 and then settling at twice the design luminosity ($\mathcal{L}$=4*$10^{32}/cm^2/s$) in 2012. During this year RICH 1 and RICH 2 saw in average ~2400 and ~2700 Cherenkov photons per event. The challenge did lie in the highly non-even distribution of the photon hits across the detector planes, illustrated in Fig. 1. This gave rise to occupancies close to the design limit of 10 % of the pixel readout chip in the most active regions. It was managed by carefully load balancing the available readout lines for best use of the available bandwidth. Eventually it also became necessary to add further off-detector readout boards receiving data from the detector regions with the highest occupancies.

Most HPD exhibited a very stable imaging over time. Only a small number of HPD were found to show movements of the image of the photocathode, which is projected onto the silicon sensor by the cross-focusing electron optics. These movements were of irregular pattern, apparently without periodicity or correlation. The image centres wondered off typically by 1.5 or maximally up to 3 pixels with typical time scales of 30 minutes to one hour involved. Fig. 2 and 3 give two examples of such image drifts. The centre of the photocathode image on the sensor of the HPD is closely monitored over a period of approximately 15 hours. One can see that the movements in x- and y-direction are correlated, but not linearly. This issue was resolved by the implementation of an automated monitoring system, fitting the image positions and correcting the movements online for every run that lasts not longer than an hour.

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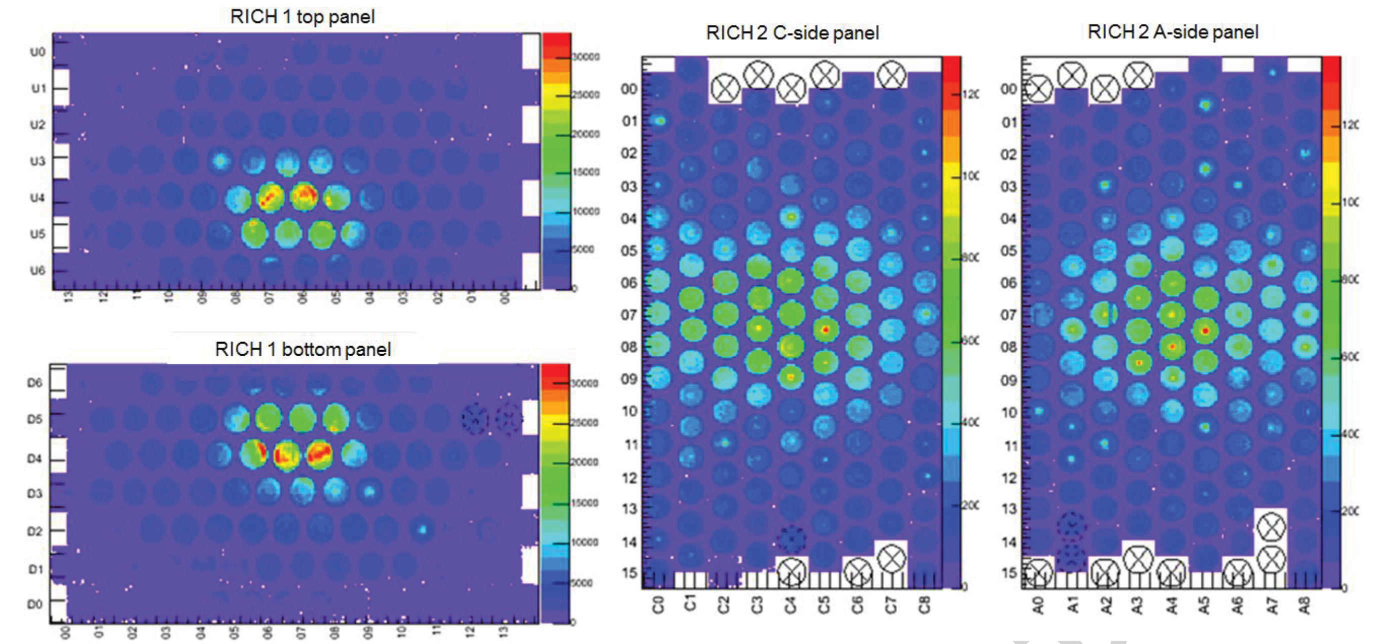

Figure 1: Typical occupancies of photon hits on the RICH detector panels during 2012, left: RICH 1 (upper and lower panel), right: RICH 2 (left and right panel).

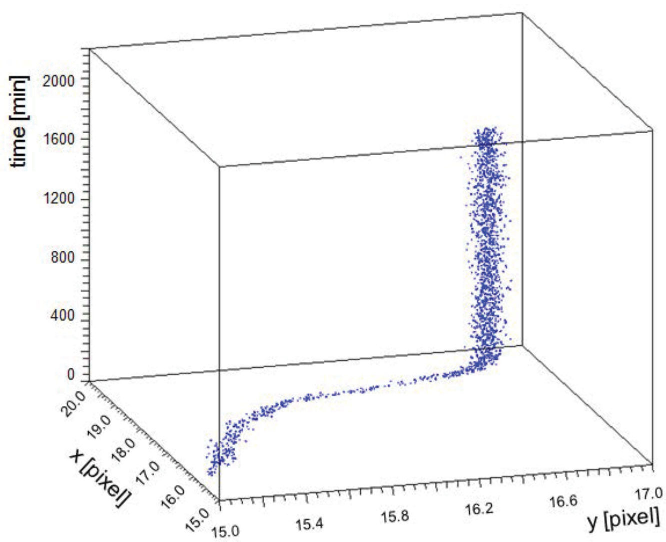

Figure 2: Drift of the centre of the photocathode image of a HPD, monitored over ~15 hours, example 1.

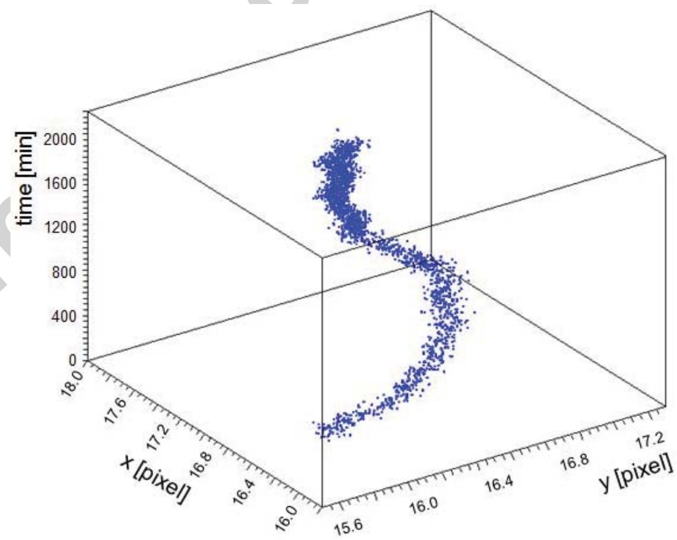

Figure 3: Drift of the centre of the photocathode image of a HPD, monitored over ~15 hours, example 2.

It seems most likely that these movements are linked to slight drifts in the electrostatic field induced by slow charging-up effects. These movements have been reproduced and studied in a controlled lab environment on the one HPD that showed the largest image drift excursion. But the actual cause has not been identified.

During the 2011 running period, while the instantaneous luminosity was steadily increasing, we started to see corona discharges, first at one RICH 1 HPD, then spreading to some of its neighbours. These discharges only occured during collisions, suggesting the build-up of charge clouds playing a role. The problem was fixed by replacing the N_2 atmosphere of the encapsulated photon detector boxes with CO_2. Although the dielectric strength of CO_2 is lower, its slight electronegativity appears to purge the volume efficiently. For safety we also temporarily lowered the HV to 16 kV and serviced the insulation of the magnetic shielding at the next shutdown. No corona was observed again.

4. Photon Yield

Measuring the photon yield in a typical busy LHCb event is difficult. Instead we selected clean samples of $pp \to pp\mu^+\mu^-$ events as a source of isolated rings generated by charged par-

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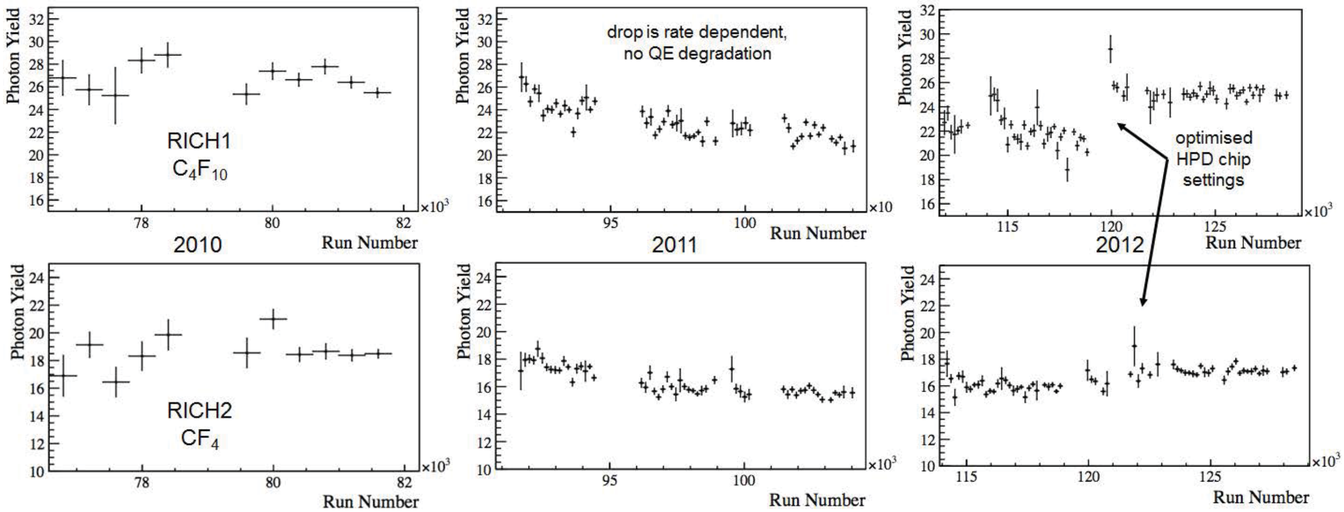

Figure 4: Photon yields of the RICH 1 (top) and RICH 2 (bottom) detectors, measured from data over the running periods 2010-2012 (left to right).

ticles with $\beta \sim 1$. The first step was to fit the shape of the Cherenkov angle resolution globally. With this shape fixed, each track in the clean sample was fitted, also assuming a flat background from uncorrelated photons. The fit then yielded the number of photons making up the ring image. This number of photons per ring image was recorded and averaged over a reasonably sized sample, typically a long run.

In Fig. 4 the results of all such measurements of the photon yields from data in the RICH 1 and RICH 2 detectors are plotted for the three running periods 2010-2012. One can notice a drop of the yields during 2011 and could suspect a degradation of the Quantum Efficiency of the photon detectors. But the drop correlated with the increase in the event rate processed in the front-end chips embedded in the HPDs. It turned out that the configuration of the chips was non-optimal for the output rate of 1 MHz, which was approached at the end of 2011. Proof is the recovery of the photon yields to nearly original values in 2012 after a reconfiguration improved the settings of the front-end chips. Tab. 1 compares the measured photon yield with

Photon Yield 2011 using	data: pp $\rightarrow pp\mu^+\mu^-$	MC: $D^* \rightarrow D^0\pi^+$ calculated	MC: $D^* \rightarrow D^0\pi^+$ true
RICH 1: Aerogel:	4.3 ± 0.9	8.0 ± 0.6	6.8 ± 0.3
RICH 1: C_4F_{10}:	24.5 ± 0.3	28.3 ± 0.6	29.5 ± 0.5
RICH 2: CF_4:	17.6 ± 0.2	22.7 ± 0.6	23.3 ± 0.5

Table 1: Photon Yields of the RICH detectors in 2011.

those calculated from Monte-Carlo (MC) simulations, using the decay channel $D^* \rightarrow D^0\pi^+$, and the corresponding uncorrected (true) values. Correcting for the loss of yield due to the high data rates we still find the data slightly too low, but overall a reasonable match.

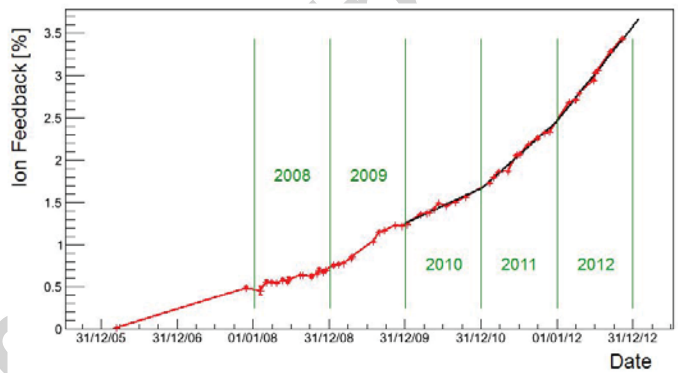

Figure 5: Ion feedback of HPD H602003, measured in-situ in RICH; the years of operation are indicated, the last three are superimposed with linear fits.

5. Ion Feedback

A particular challenge to the HPDs is the rate of vacuum degradation a fraction of the tubes is suffering from. This is further compounded by the correlation of the degradation speed with the increasing luminosity. Before the operation in RICH, we found the bulk of the HPDs to evolve with a slope, δ_{IFB}, of less than 0.5 % per annum and only very few HPD evolving more quickly. But operating the tubes regularly in the RICH system from 2009 started to increase the slope for most HPDs. This is exemplified in Fig. 5 with the IFB evolution for one HPD. The data was gathered in the long-term in-situ IFB monitoring programme for all HPDs the RICH system [7]. Over the subsequent running periods the slope δ_{IFB} then increased further in correlation with the increases of the instantaneous luminosity LHCb was taking. The luminosity correlates with the occupancies and in turn with the data throughput. The data throughput drives the power dissipation in the embedded read-out electronics. This way the increase of the taken luminosity leads to the recorded increase of the operating temperature of HPDs. And this increase in temperature is the suspected cause for the increase in the IFB.

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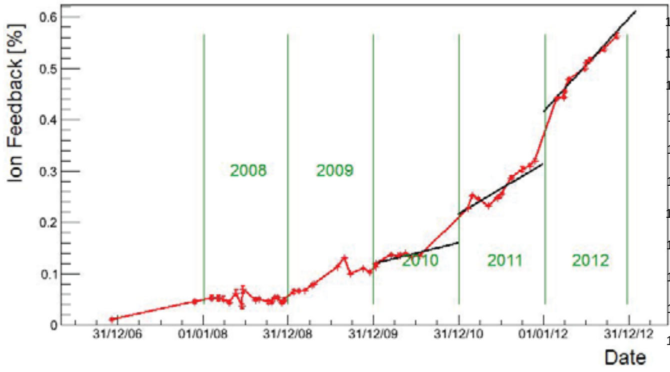

Figure 6: Ion feedback of HPD H638003, measured in-situ in RICH; the years of operation are indicated, the last three are superimposed with linear fits.

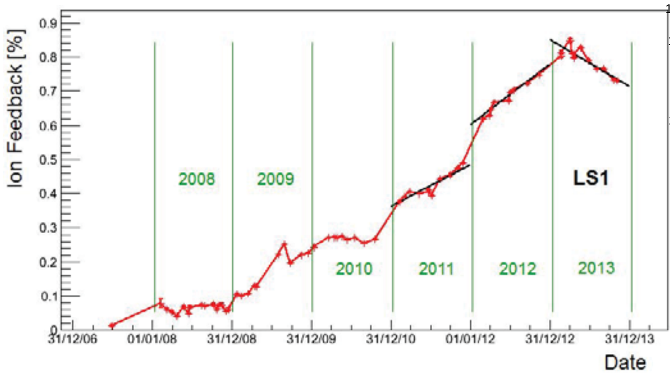

Figure 7: Ion feedback of HPD H721002, measured in-situ in RICH; the years of operation are indicated, the last three are superimposed with linear fits.

In general IFB is neither a problem to the operation of the HPDs nor introduces it additional background to the particle identification. As they are late the IFB clusters only add random hits to later events. And to random hits the particle identification algorithms are insensitive. Only if the threshold is passed where the secondary electrons become likely to initiate further IFB events the perpetuating cycle of IFB is started. This lets the photocathode degrade quickly and the tube becomes very noisy. The ongoing online-monitoring and repair programme assures the timely exchange of HPDs before they reach this threshold. But even if that would be missed, an HPD in the state of perpetuating cycle of IFB still provides valuable photon data outside its centre area, where the IFB concentrates. A single such HPD also does not significantly affect the operation of the rest of the detector. Two such HPDs per column would be a limit not to exceed.

A second effect, demonstrated in Fig. 6, is that a fraction of HPDs now evolve even more quickly during the shutdown periods, i.e. when all supplies are switched off. This typically is seen with HPD which still have an overall low IFB, below 1 %. The interpretation is, that when switched off no annealing is taking place, i.e. there are no photoelectrons passing the volume which could ionise residual gas atoms, which subsequently attach to inner surfaces or the HPD. Such annealing only is visible if the intrinsic increase of IFB is not too large.

To counter this behaviour we have adopted operation conditions for the time of the long shutdown in 2013/14 which maximise the effect of annealing. The embedded readout electronics is switched off to minimise the heat. The HV is left on and the HPD are illuminated moderately with a cw-laser to keep the annealing process active. And the biasing of the sensors is left on to allow for continuous monitoring. Fig. 7 is demonstrating the profound effect this has on HPDs with not too high IFB. It appears that the annealing is outweighing the intrinsic IFB increase. The absolute IFB is decreasing over time. Over 2013 163 HPDs did experience a decline in the absolute IFB, 144 HPDs did show at least a reduction in the increase δ_{IFB}, 97 continued with the same slope and 9 HPDs did show a slight increase in the slope, with these groups coarsely ordering from low to high in absolute IFB. About 50 other tubes in RICH 2 cannot be properly illuminated by the cw-laser light and are not counted above.

6. HPD Optimisation

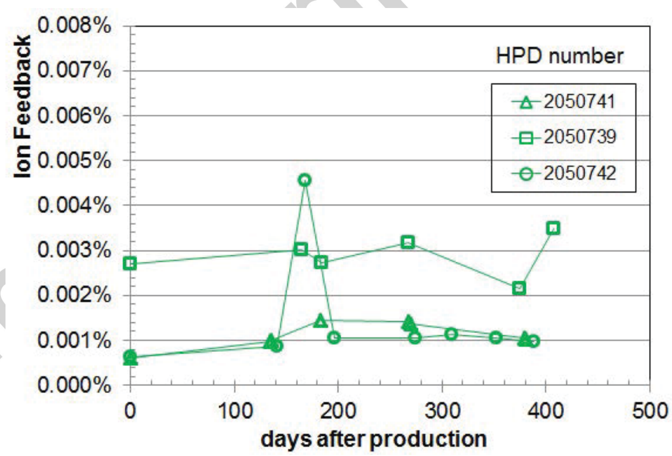

Figure 8: Flat IFB evolution of HPDs with getter strips over a year.

The problem with the evolving IFB casts a shadow on how this technology is regarded, despite its excellent performance otherwise. Furthermore the number of available anodes and how often they can be reprocessed in a repair procedure is limited. To counter both a HPD variant was developed which suppresses the intrinsic IFB by introducing getter strips into the volume of the tube. They are properly activated with a changed bake-out procedure, while maintaining the constraints given by the delicate structure of the anode. The getters are dimensioned to last in excess of the projected life time of the HPDs.

That this effort was successful can be seen from Fig. 8 where the IFB evolution is plotted for the first three HPDs with getter strips over a year after their production. The IFB of these HPD shows no increase and stays at the extremely low level of IFB = 0.001-0.003 %. This is very close to what can be resolved using the methods available at the HPD test centres [6], which are more sensitive than the in-situ measurements in the RICH system. For comparison, good HPDs with low IFB increase, but without getters, typically showed IFB =0.01-0.1 %

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after production and evolved with rates between δ_{IFB}=0.1-0.2 % per annum.

7. Conclusion

The HPDs bring two great virtues, the high Quantum Efficiency and low noise and background. We got the operational challenges during Run 1 quickly under control or well managed. We developed reliable tools and measures to deal with the IFB of the HPDs, so that the excellent PID properties of the RICH detectors are not affected. And finally we have now developed a long-term fix to suppress the IFB in the HPDs and use that in the current repair programme in preparation for Run 2.

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